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13. ABSTRACT (Maximum 200 words)

Superconducting Quantum Interference Devices (SQUIDs) have been studied to determine their suitability for use as qubits in quantum computers. It has been demonstrated, using spectroscopic measurements, that it is possible to place such a SQUID in a coherent superposition of “0” and “1” quantum states as required for use as a qubit. A transformer for the controllable coupling of flux qubits (one of the key components needed for a quantum computer) has been developed. Theoretical techniques for the analysis of experimental, multilevel qubit systems have been developed. Analysis has been done for Aharonov-Casher qubits that allow access to all key variables and for quantum-limited JJ comparator readouts. The theory of linear detection has been extended to quadratic detectors. Our fabrication capability has been upgraded to yield high-quality Nb qubits (less than 1 pA subgap leakage current at 0.3 K) with a 1 week turn around.

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Problem studied.

The major goal of this project has been to investigate the suitability of SQUID qubits as a technological basis for quantum computing (QC). The theoretical part of the work has focused on how to use such qubits for key operations in QC, e.g. error correction and readout, as well as more basic problems such as the theory of quadratic detection. Experimentally, we have demonstrated that the required coherent superposition of computational states of a SQUID can be achieved and investigated limiting factors for this coherence. Methods for controllable coupling of flux qubits have been developed and our niobium fabrication technology has been modified to provide the ultra-high quality junctions and rapid turn around required for qubit development.

Summary of results.

- **Theory**

Theory results include the suggestion of a qubit design based on the Aharonov-Casher effect for flux tunneling, and the extension of the concept of the quantum non-demolition measurements to the measurement of the macroscopic quantum coherent oscillations in an individual qubit. Many approaches to Josephson-junction qubits, e.g., attempts to implement schemes of ground-state quantum computation, require the possibility of external modulation of not only the magnitude but also the phase of the flux tunneling amplitude in a flux qubit. The possibility to control the phase is not provided by basic qubit designs proposed and implemented up to now. We suggested a simple system, ``a charge-controlled SQUID", which allows one to control the phase of the flux tunneling amplitude. The system consists of a Bloch transistor included in the superconducting loop with finite inductance and uses the Aharonov-Casher effect to modulate the flux tunneling amplitude. The Aharonov-Casher effect in a simple system of Josephson junctions is of considerable interest of its own, and we expect that the suggested qubit design will be useful for Josephson-junction quantum computation in many different contexts.

One important application of the Aharonov-Casher effect in the charge-controlled SQUID is the technique of nondemolition measurements of the macroscopic quantum coherent oscillations in an individual qubit. In regular (non-QND) measurement strategies, coherent oscillations are suppressed by the detector back-action even in the case of the quantum-limited detectors. This makes it impossible to directly observe quantum oscillations in a qubit. The QND technique developed for a qubit in this work enables one to avoid the detector back-action and measure the qubit oscillations directly. It requires, however, the ability to measure at least two non-commuting observables of the qubit. In JJ qubits, this in turn requires a non-trivial qubit design that makes possible the measurements simultaneously in the charge and flux basis. The Aharonov-Casher effect in the charge-controlled SQUID allows this type of measurements by coupling the dynamics of flux and charge. Besides being of fundamental interest, QND measurement techniques hold promise for the development of error-correction in Josephson-junction qubits.

Further theory work under this grant focused on the study of quantum measurements with mesoscopic detectors. One focus of this effort was extension of the previously developed theory

of linear quantum detectors to the quadratic regime. Quadratic detectors are of interest for quantum information processing in solid-state qubits since they should enable measurements of product operators in the two-qubit structures. Potential applications of this property of quadratic detectors include creation of entangled two-qubit states and simple schemes of error-correction. We have developed a quantitative theory of mesoscopic quadratic detection. The theory is based on the understanding that the operating principle of the typical mesoscopic detector is controlled by the measured system of the amplitude of transition between the two reservoirs of some particles, e.g., electrons, Cooper pairs, or magnetic flux quanta. If the transmission amplitude is insensitive in the linear order to the control parameter of the measured system, then the detector measures only the square of the coupling operator. This unified approach to mesoscopic quadratic detection shows that quadratic detectors can be quantum-limited when the detector operates with minimum quantum mechanical back-action. The quantum-limited nature of the quadratic detection should manifest itself in the observed spectra of the quantum coherent oscillations in the two-qubit systems.

A general method has been developed for the calculation of quantum fluctuation effects for damped harmonic oscillators with arbitrary time dependence of frequency and for arbitrary temperature, within the Caldeira-Leggett model. This method has been applied to analyze quantum limited comparators for the measurement of flux qubit states. Fast, single-shot quantum measurements of the final state of “output” qubits are an important part of any quantum information processing scheme. Among scalable, solid state circuits which can perform such measurements, the superconductor "comparator" based on two similar, over damped Josephson junctions (Fig. 1) stands apart as a simple, scalable system.

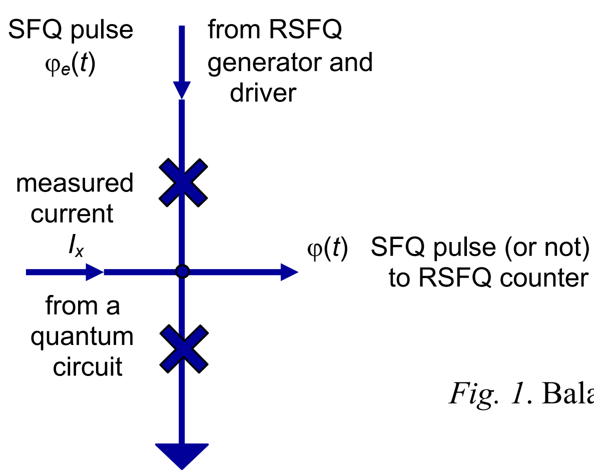

Fig. 1. Balanced Josephson junction comparator.

The device is essentially a dc SQUID in which the junctions are biased in series by a source of Josephson phase difference $\varphi_e(t)$ and in parallel by the current Ix to be measured. A special RSFQ circuit feeds the comparator with single-flux-quantum (SFQ) pulses. Each pulse rapidly changes the applied phase φ_e by 2π. As a result, the system becomes statically unstable and the “output” phase φ switches to one of two stable states, depending on the sign of Ix. In the absence of fluctuations, the boundary between these two outcomes is sharp; however, fluctuations create a finite "gray zone" of width ΔI_x in which the probability of switching to a

certain state changes gradually from 0 to 1, so that ΔI_x characterizes the comparator sensitivity for single-shot measurements.

This width and its temperature have been measured in several special experiments with externally-shunted LTS Josephson junctions. However, theoretically it had been only calculated for a special time dependence of $\varphi_e(t)$, enabling (quasi-) analytical solution of the problem, but rather different from those used in experiments. For this reason, quantitative comparisons of theory and experiments have been rather inconclusive.

We have developed a general method of calculation of quantum fluctuation effects, in particular, in the gray zone of instability of frequency sign inversion, for damped harmonic oscillators with arbitrary time dependence of frequency and for arbitrary temperature, within the Caldeira-Leggett model. The method has been applied to the balanced comparator, driven by the real waveform $\varphi_e(t)$ generated by an RSFQ comparator.

The results for the gray zone width ΔI_x are in a virtually perfect agreement with experimental data for Nb-trilayer comparators with critical current densities of 1.0 and 5.5 kA/cm2, -- remarkably without any fitting parameters. These results confirm that Josephson junction comparators can really work as fast, quantum-limited instruments for measurements of fixed electric current. The issue still to be studied is the back action effect of the dissipation in Josephson junctions of the comparator on dephasing in the measured quantum circuit.

- **Experimental**

The coherent superposition of macroscopically distinct quantum states of a Superconducting Quantum Interference Device (SQUID) has been demonstrated. These results have important implications both for our fundamental understanding of quantum mechanics and for the development of quantum computers based on superconducting components or qubits. In 1935, Schrödinger attempted to demonstrate the limitations of quantum mechanics through a thought experiment in which a cat is put in a quantum superposition of alive and dead states. While much progress has been made in demonstrating aspects of macroscopic quantum behaviour of various systems, the results summarized here provide the first experimental evidence that a truly macroscopic system (the SQUID) can be put into a coherent superposition of states: one, a few microamperes of current flowing clockwise; the other, a current of equal magnitude flowing counter-clockwise. Of great technical importance, these two states have the potential for serving as the $|0\rangle$ and $|1\rangle$ states for a qubit of a quantum computer. Success in developing such a solid state qubit would mean that it should be possible to use standard integrated circuit techniques to assemble a group of qubit large enough for useful computation.

The SQUID is a superconducting loop of inductance L broken by a Josephson tunnel junction with capacitance C and critical current I_c. In equilibrium, a dissipationless supercurrent can flow around this loop, driven by the difference between the flux Φ that threads the loops and the external flux Φ_x applied to the loop. The dynamics of the SQUID can be described in terms of the variable Φ and are analogous to those of a particle of "mass" C moving in a one-dimensional potential given by the sum of the magnetic energy of the loop and the Josephson coupling energy of the junction. When $\Phi_x = \Phi_0 / 2$ (Φ_0 is the flux quantum) the potential is symmetric with an

energy barrier ΔU_0. Any change in Φ_x then tilts the potential by ε. For weak damping, the system has quantized energy levels that, well below the barrier, are localized in each well. At various values of Φ_x, levels in opposite wells will align, giving rise to resonant tunnelling between the wells. During this interwell transition Φ changes by some fraction of Φ_0, or – stated in different terms – the magnetic moment of the system changes by a macroscopic amount, over 1010 B. This change in Φ can be detected using a magnetometer coupled to the SQUID. Until now, however, there has been no evidence that the tunnelling process between these macroscopically distinct states could be coherent, that is, that the SQUID could be put into a coherent superposition of two flux states in different wells.

Such a coherent superposition of two flux states in different wells would manifest itself in an anticrossing of energy levels for the two levels of different wells ($|0\rangle$ and $|1\rangle$) in the neighbourhood in which they would become degenerate without coherent interaction. Coherent tunnelling lifts the degeneracy) so that at the degeneracy point the energy eigenstates are $\frac{1}{\sqrt{2}}\left(|0\rangle+|1\rangle\right)$ and $\frac{1}{\sqrt{2}}\left(|0\rangle-|1\rangle\right)$, the symmetric and anti-symmetric superpositions. In these experiments, the anti-crossing of two excited levels in the potential was probed by using microwaves to produce photon-assisted tunnelling.

The system was initially prepared in the lowest state in the left well ($|i\rangle$) with the barrier high enough that the rate for tunnelling out of $|i\rangle$ was negligible on the time scale of the measurement. Then, with ε (Φ_x) and ΔU_0 fixed, pulsed microwaves at 96 GHz were applied and the probability of a transition measured. The experiment was then repeated for a range of ε (Φ_x) and ΔU_0. For certain values of these parameters, peaks in the transition probability were seen, indicating the presence of a level with an energy 96 GHz above that of $|i\rangle$. These data clearly show the anti-crossing predicted by the solution of Schrödinger's equation for this potential in the zero damping limit. All data correspond to levels that are below the top of the barrier. The importance of this is that the flux basis states $|0\rangle$ and $|1\rangle$ are macroscopically distinct with mean fluxes that differ by about ¼Φ_0. Each observed anti-crossing thus represents the coherent superposition of macroscopically distinct states.

To summarize: The energy level spectrum of a SQUID has been measured near the crossing point for levels with macroscopically distinct magnetic moments. The measured spectrum agrees well with that expected from a coherent superposition of these levels. These results demonstrate the prospect for using SQUIDs as qubits in quantum computers and extend the tests of quantum mechanics into a new regime.

The subsequent experimental work has focused on the development of a set of basic techniques and devices that have sufficiently high quality that they will be a solid, scalable foundation for building more complex quantum circuits. Several aspects of this work are: i) development of low-loss tunable transformers for coupling of flux qubits, ii) design and testing of specialized filters to provide a high level of isolation from the decohering effects of external circuitry while permitting coupling of very fast control and readout signals to the qubit, iii) developing techniques for the measure of key properties of niobium junctions as part of an effort to optimize

qubit quality using refractory metal junctions, iv) process development to optimize fabrication techniques to achieve the longest possible coherence times in Nb qubits.

One of the key components needed for a quantum computer is a controllable coupling circuit between the qubits. We have developed a design for such a transformer for flux qubits, fabricated a prototype and made initial tests on it. A key feature of the design is that this circuit should have very low damping in both the on and off states. When the inductances of the two legs of the transformer are equal, ideally the coupling is zero. In order to unbalance the transformer and provide tunable coupling, the control flux Φ_c through one of the dc SQUIDs is changed. This changes the Josephson inductance of that arm and unbalances the transformer.

We are working to optimize our niobium process for QC applications. In particular, what is needed for the present stage of QC development is a process that can produce small scale circuits with rapid turn-around and that will yield qubits with the lowest possible dissipation. It is known, for example that RIE, which is commonly used in niobium trilayer processing introduces some degree of damage. For classical circuits this is not significant. However, it can seriously degrade the coherence time in qubits. In addition, other fabrication induced defects such as 1/f fluctuation in I_c , subgap leakage and excess surface resistance in niobium films all contribute to decoherence. As part of this project we are measuring the effects and optimizing our processing to reduce them. To address these issues, the following improvements have been implemented in our processing.

- New self-aligned liftoff with e-beam lithography (SAL-EBL) process developed.
- Short turn-around time (4-5 days /wafer)
- Use of negative e-beam resist for junction definition: Nb/AlOx/Nb trilayer and Nb wiring layer patterned with lift-off.
- Only 1 metal etch step to reduce RIE damage.

We are now fabricating circuits with $J_C \sim 100$ A/cm^2 to 300 A/cm^2 processed with a minimum junction size of $0.3 \times 0.3\,\mu$m

Measurements of junction quality for this process have been made. The low-voltage (0-50μV) subgap leakage, determined either fundamentally by BCS theory or by fabrication-induced barrier defects, poses a limit to the coherence time of qubits. In order not to be a significant limit for the near future this implies a low voltage resistance of about 1 GΩ. At temperature below about 0.5 K, the BCS resistance will be greater than this, thus barrier defects are the only real limit. This leakage has been measured to 0.3K using the higher quality junctions resulting from the upgrading of our processing. We find that the low voltage (down to about 300μV) resistance is above the required value of 1 GΩ. It now seems as though Nb junctions are very good qubit candidates.

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Submitted for publication

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